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Revolutionary Technologies for Gun-Launched Miniature Measurement Systems

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Abstract

A survey of telemetry techniques for miniature and high-g applications is provided. The sum of many individual efforts is providing an expanding set of tools and techniques by which a new generation of flight tests is possible. Additionally, major thrusts have been made to substantially reduce the cost of key components and modules of the telemetry system. New capabilities in transmitters, power supplies, electronic packaging, and sensors are being developed.

Acknowledgments

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1. Background

With the ever-increasing sophistication of missiles, projectiles, and munitions, flight tests are expected to help understand performance and to contain development costs. However, in the case of small or relatively inexpensive high-g systems, flight tests are often not made due to the anticipated or presumed high cost of measurement systems. Although special high-g telemetry systems exist, their usage is not as common as in larger, more expensive, non-high-g systems. The Hardened Subminiature Telemetry and Sensor System (HSTSS) Program has been jointly sponsored by the Department of Defense (DOD) and the U.S. Army to develop and demonstrate a new generation of high-g telemetry technologies and to make these products available to the test community (Faulstich, Burke, and D'Amico 1996). Additionally, the Commercial Technology Insertion Program (CTIP), being sponsored by the Office of Naval Research (ONR) is funding demonstration efforts that are focused on microelectromechanical systems (MEMS).

2. Difficulties in Free-Flight High-g Telemetry Systems

It is obvious that the telemetry transmitter/antenna, supporting electronics, and power supply must be able to withstand the shock of the launch environment. However, the fundamental problem often involves the sensors. The sensor systems must essentially be dual in nature. Some must only survive the launch/boost environment and then make a measurement during the "ballistic" portion of the flight, while other sensors must make a measurement during the launch/boost phase. Also, most projectiles and small missiles have "continuous" roll rates. The presence of continuous roll can yield a bias in a direct-current (DC) sensor, thus reducing accuracy and modifying the measurement range. Continuous roll can also lead to significant phase errors in roll position if an angular-rate sensor is used.

3. Power Sources

A fundamental difficulty in any free-flight measurement system is the source of power. Typically, nickel cadmium (NiCad) or thermal batteries (in case of large, power requirements) are used. Often, however, batteries for high-g telemetry systems are not significantly different than the batteries that are available in drug stores.

HSTSS is developing and testing several power-cell technologies for high-g use. Solid polymer, lithium-ion power cells from Ultralife Batteries (UK) have been under evaluation (Burke, Faulstich, and Newnham 1995). These batteries (nominal 4 V) are rechargeable, physically configurable, and environmentally friendly. Cells can be made to almost any user shape or configuration. Single-cell configurations have survived shock accelerations of more than 110,000 g's and centrifugal tests at 300 rps, yielding radial accelerations of 24,000 g's. Research, sponsored by the Defense Advanced Research Projects Agency (DARPA), is currently being performed by Ultralife Batteries to increase the cell energy density and temperature performance. Primary power cells, available from Ultralife Batteries (U.S.), offer similar form-factor characteristics with even higher energy density. Figure 1 shows some specific cells that have been developed and tested.

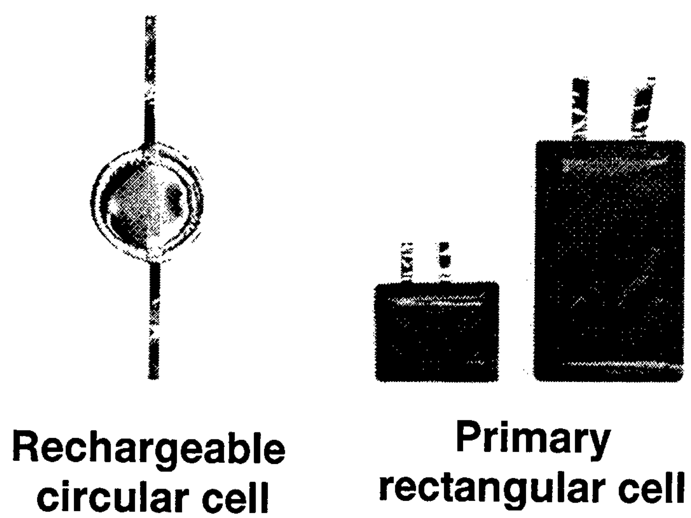


Figure 1. Solid Polymer Power Cells of Various Geometries and Chemistries.

4. High-Density Electronic Packaging

The industry trend to miniature electronic packaging must be leveraged. Clearly, one-of-a-kind telemetry systems cannot be directly produced using the common industrial high-density packaging practices that have evolved for mass production.

Multilayer, printed, circuit board technology is the most common format for electronic packaging, but higher density packaging techniques exist. These methods are typically called multichip-modules (MCM), but they can involve long and costly design and manufacturing processes. Two commercially available MCM technologies have been under evaluation as packaging alternatives (Burke et al. 1995). Both of these MCM technologies are electrically programmable and allow for the direct placement of a raw die (the unpackaged, integrated circuit component) onto a premanufactured substrate. One substrate technology by PICO Systems uses an antifuse technology and is silicon based. Circuit connections within the substrate are programmed by disabling the antifuses to produce internal circuit paths or vias. The dies are then attached by normal wire-bonding techniques to the substrate. A PICO Systems MCM package (shown in Figure 2) has been flight-tested at an acceleration level of 20,000 g's with both analog and digital components as part of the measurement system.

A second vendor, Microelectronics Computer Technology Corporation (MCC), offers a rapid prototyping technology that utilizes a laser customization tool, creating custom circuitry on a generic thin-film substrate. As before, the dies are attached to the MCM using standard wire-bonding methods. These substrates offer a wide variety of geometrically flexible shapes and high packing densities. Bare substrates from MCC have survived laboratory shock testing in excess of 30,000 g's.

Both of these technologies are cost effective as low-volume (one-of-a-kind prototypes to several hundred units), high-density, MCM schemes. An HSTSS-sponsored packaging study is currently underway to further examine these technologies and compare them to more common industry MCM processes.

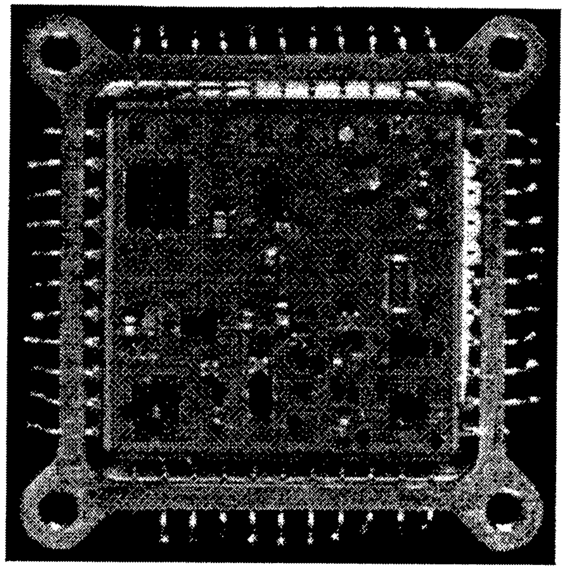


Figure 2. Programmable MCM.

5. Transmitter

Multiple solutions to the data transmission problem are being studied. Technical, operational, and fiscal factors contribute to this issue's resolution. Range infrastructure and frequency allocations and existing telemetry ground stations must be used. The high-g and small size requirements may not meet all existing compatibility requirements (frequency, stability, etc.), but low power and short transmission times will most likely allow for practical use via "exemptions."

The portable-communications industry is rapidly developing new devices and products. Wireless communication systems, local area networks, cellular phones, and mobile links are common at frequencies not permitted on test ranges. However, existing, commercial, communication technologies have promise for applications at L- and S-band frequencies (approximately 1.5 and 2.2 GHz). Preliminary evaluations indicate that these technologies can be made compatible with the standards of frequency allocation, stability, and bandwidth. HSTSS is presently in the process of awarding a commercial contract to M/A-COM for a new family of miniature, high-g, low-cost transmitter (XMTR) components and modules.

6. Comparative Data Sources: Radars and Yawsondes

If improvements are to be made, then any new measurement must be compared against accepted standards. The primary standard for range time-space position information (TSPI) has been radar. Laser and optical trackers are also used, but reasonably portable and affordable Doppler radar systems are in common use.

On the other hand, radars do not provide good angular resolution. The typical "skin track" simply provides an estimate of the center of mass translational motion, not the angular motion. A common technique known as a yawsonde can provide very accurate measurements of pitch, yaw, and roll. The yawsonde (shown in Figures 3 and 4) is an electro-optical unit that uses the sun as a reference to measure angles. The yawsonde includes a number of silicon photosensitive cells (solar cells) held in a fixture that defines the optical field of view (FOV), signal-conditioning circuits, a voltage-controlled oscillator (VCO), and a transmitter/antenna/power supply system. A yawsonde measures the angle between the projectile roll axis and a vector drawn from the center of gravity of the projectile to the sun, the solar angle.

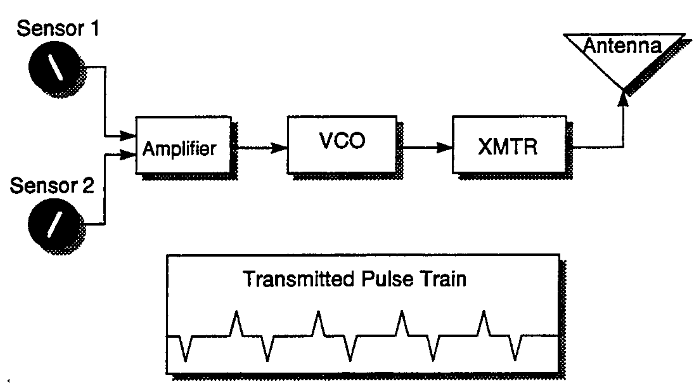
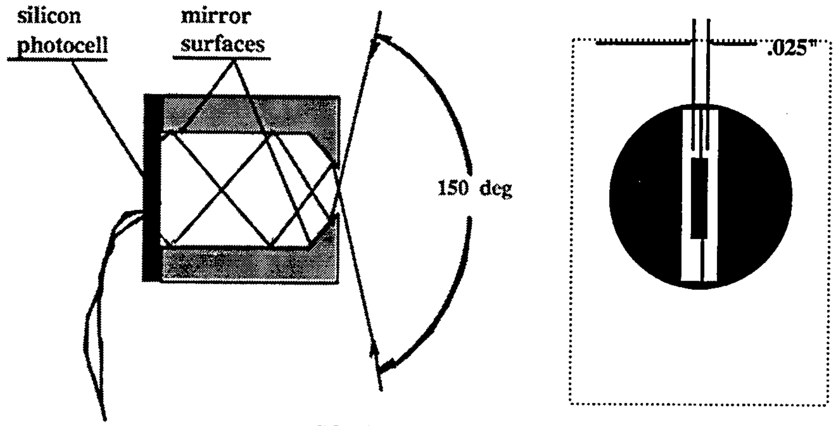


Figure 3. Basic Description of a Yawsonde System.



SOLAR SENSOR

Figure 4. Typical U.S. Army Research Laboratory (ARL) Sun Sensor Configuration.

This angle varies as the projectile travels along the trajectory and as the projectile yaws. The optical FOV is arranged to yield a "V" in space. Each "leg" of the V is coded to a particular optical sensor (one positive and one negative in output voltage). The yawsonde is calibrated in an optical bench such that the V is presented at various fixed angles to a collimated light source. The relative crossing points on the V for each sensor are then related to the angle made to the light (which, in flight, would be the sun). It now is only required that the number of sightings to the sun (the number of solar cells) satisfies basic sampling theory (i.e., the roll frequency must be at least twice as fast as the yaw frequency) (Mermagen and Clay 1974).

Typically, yawsondes are built in the configuration of an artillery fuse for use with projectiles. However, yawsonde technology has been applied to slower rolling airframes, such as the 155-mm M712 Copperhead and 2.75-in rockets (Brown 1989; Brown et al. 1996). Since a yawsonde system directly measures both fast and slow yaw frequencies and the roll rate, a direct computation of static moment coefficient can be made. Also, complete roll histories naturally yield the roll, damping moment coefficient. Whyte and Mermagen (1973) used yawsonde and radar data linked to a six-degree-of-freedom (6-DOF) model to establish other aerodynamic coefficients. Most recently, a similar but updated methodology was used to analyze 2.75-in rocket data (Brown et al. 1997).

A unique implementation of yawsonde technology was demonstrated for slender kinetic energy (KE) projectiles (Ferguson and Hepner 1996). In the near future, a free-flying magnetometer experiment will utilize a new optical design and will be conducted by the Jet Propulsion Laboratory (JPL) (Hepner, Hollis, and Mitchell 1997). It is clear that the routine use of yawsonde technology with other sensors could be very useful. However, solar testing windows are sometimes restrictive for various applications (if unusual trajectory shapes or dynamics occur due to maneuvering munitions); finally, the sun must be shining. It is clear, however, that yawsonde systems will be used as a standard of comparison for emerging angular-rate sensors or other angle measurement systems.

7. Miniature Sensor Technology

Sensor technology is undergoing a rapid evolution as advanced materials and materials processing are focused to yield new measurement devices. A major area of interest is the so-called MEMS industry. Major investments on the part of DARPA have been made in MEMS. A MEMS device typically uses integrated circuit materials and processes to produce an extremely small mechanical system (a sensor die) that responds to linear or angular motion, accelerometers, and gyroscopes. The sensor die is then integrated with a miniature electronic system (an electronic die) to measure the mechanical motion of the sensor die and to convert that motion into signals that are in turn translated into engineering quantities. The highly integrated sensor and electronic dies form a MEMS. The most common MEMS device is an accelerometer. These 5- and 50-g range accelerometers are extremely small, highly sensitive, and inexpensive (Goodenough 1991; Ridel 1993).

Analog Devices Incorporated (ADI) has produced a family of accelerometers that is typically the size of a pencil eraser, costs about $15, and has milli-g sensitivities. MEMS accelerometers of this type represent an order of magnitude improvement in miniaturization and cost. MEMS pressure transducers are also available. Leveraging the MEMS industry is the key to revolutionizing measurement technology for free-flight systems. A discussion of sensor combinations and uses follows.

8. Roll Position and Roll-Rate Sensors

A rolling motion is a unique type of angular motion. Typically, in small missiles and fin/spin-stabilized projectiles, the roll rate is a continuous value with slow decay or modulation caused by aerodynamic effects. Measurement of this type of roll rate is not easily accomplished by classical angular-rate sensors. Scale-factor errors will quickly accumulate, and roll-orientation accuracy will be lost. It is then preferable to use a sensor that does not possess large, scale-factor errors. The yawsonde, for example, does not accumulate roll position errors in the measurement process. The duty cycle of data from one sensor easily forms a good approximation to the Eulerian roll rate.

Magnetic sensors have long been available. Repeatable amplitude calibrations and the presence ferrous materials can result in difficulties, but magnetic sensors can be effectively used to measure roll in free flight. The SCSA50 is a magnetic, angular-rate sensor that provides one count per revolution on an object that is spinning in free space. SCSA50s were provided to the HSTSS program by Sensor Applications for high spin and high-shock testing (Davis, Harkins, and Burke 1996). Both digital and analog signal outputs are available. A comparison of spin data from a yawsonde and the giant magnetoresistance ratio (GMR) SCSA50 is shown in Figure 5. The final form for the sensor will most likely be a plastic, dual-in-line, eight-pin package. Ground testing of encapsulated units has demonstrated survival of shocks as large as 110,000 g's.

The SCSA50 is a bridge circuit using four GMR resistive elements: two shielded and two unshielded. The output of the bridge is related to the angle that the unit makes with a magnetic field vector. A change in angle results in a change in bridge output. If the orientation to the magnetic field vector of the unit remains constant during a roll period, then the output of the bridge will not change. This measurement null zone (approximately 4°) can be reduced if the sensitivity of the

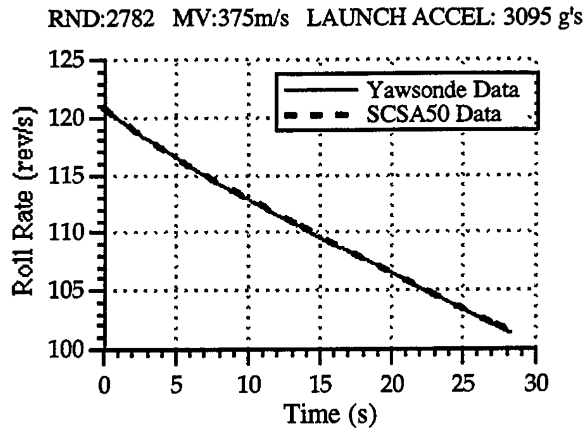


Figure 5. Comparison of Spin Data for a Magnetic Sensor and a Yawsonde.

device is increased or if multiple sensors are used. Efforts are now underway to examine new magnetic-sensing technologies that use MEMS technologies (Wickenden et al. 1997). With greater sensitivity and the efficient placement of multiple sensors at different orientations on the same device, the feasibility of accurate roll attitude and angular orientation is extremely high (Harkins and Davis 1997).

9. Linear Accelerometers

Presently, there are many manufactures of MEMS accelerometers. Some of the first commercially available devices were the ADXL05 and ADXL50 from ADI. The ADXL50 is a ±50-g device with a 30-mg resolution. An early free-flight demonstration was made on a 2.75-in HYDRA 70 rocket/warhead combination (Brown et al. 1996). A single sensor was used to measure the axial force history of the 2.75-in rocket from launch, through motor burn (maximum acceleration of approximately 70 g's), and during ballistic flight. The ADXL50 is a closed-loop sensor that can be double-ranged to 100 g's by doubling the supply voltage. Shock testing has demonstrated survival up to nearly 30,000 g's powered and to nearly 60,000 g's unpowered (Davis 1996).

A second generation of MEMS accelerometers is being offered in a surface-mount package by ADI, the ADXL105, 150, and 250 units (5-, 50-, and 2-axis 50 g's). The second-generation ADI products are open-loop devices. ADI, Motorola, and Endevco accelerometers are currently under test at ARL. The performance for some of these newer MEMS should be vastly improved, given that the accuracy of the ADXL150 is nearly the same as that of the ADXL05. It is not yet established whether the new open-loop designs are as well suited to recover from high shocks as the closed-loop designs.

It is imperative in cases of continuous spin that care be exercised to locate axial and transverse accelerometers as near to the spin axis as possible. If that is not the case, then even small offsets can yield significant bias errors due to high centrifugal forces. For an axially aligned accelerometer, the cross-axis sensitivity limits this error to only a few g's. In the case of transverse accelerometers, the bias can consume the entire measurement range of the device. Bias errors due to spin can be calibrated prior to a flight test, and the direct measurement of spin can be used to compensate for these effects. Flight measurements of axial force have been made, and comparisons with radar data or trajectory codes are presented for 155-mm projectiles and 2.75-in rockets (see Figures 6 and 7) (Davis, Harkins, and Burke 1996, 1997; Brown et al. 1997).

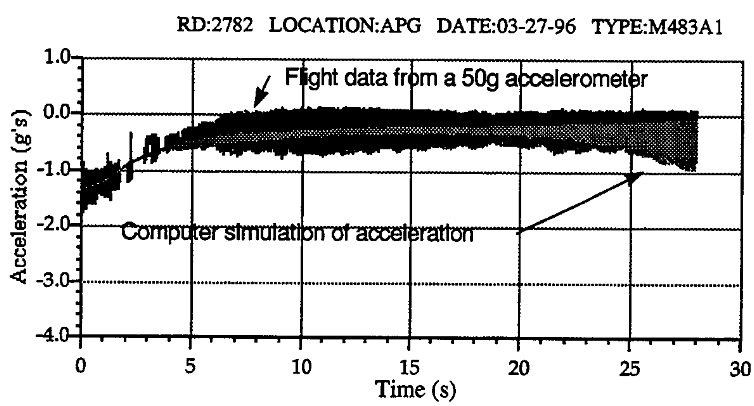


Figure 6. MEMS Accelerometer Data from a 155-mm Projectile.

10. Pitch/Yaw-Rate Sensors

Angular-rate sensors are also being produced by the MEMS industry. However, the maturity of these devices is not as great as the accelerometers. Given sufficient volume and a choice of physical

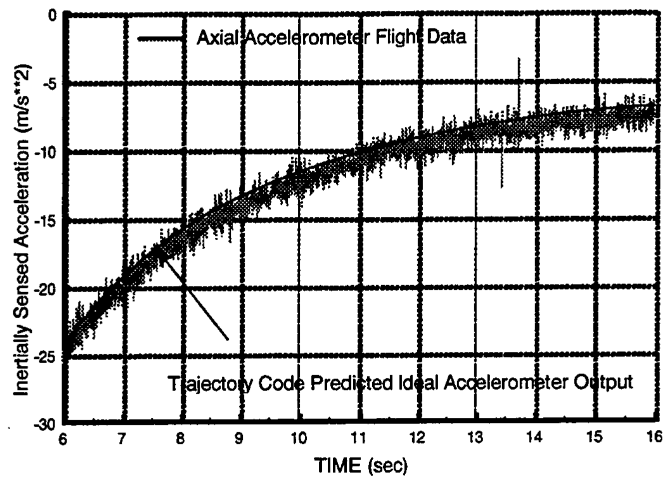


Figure 7. MEMS Accelerometer Data From a 2.75-in Rocket.

locations for a measurement system, it would be possible to use a constellation of six or nine accelerometers to derive angular rates. Due to instrumentation resolution problems, however, this can be problematic if high spin rates exist or if the accelerations in all directions are not nominally the same order of magnitude (Harkins 1994). It is preferable to perform a direct measurement of angular rate, and the need for good angular-rate sensors will remain.

Most miniature angular-rate sensors (gyros) will operate on the "tuning-fork concept." The fork is designed to vibrate and is forced at a known frequency. Due to angular rotation of the device at an orientation perpendicular to the major axis of the tuning fork, the vibration frequency will be slightly changed (a Coriolis effect). MEMS tuning-fork gyros are undergoing preliminary testing and have shown good operational characteristics. Devices from a DARPA-sponsored Technology Reinvestment Program (TRP) led by a Boeing/Draper team are providing miniature sensors that are based upon automotive applications. The input range of the automotive devices must be increased to accommodate typical angular rates for projectiles and missiles, and packaging designs must be demonstrated to be high-g compliant. These issues are being addressed under the TRP. Again care must be exercised in using these MEMS devices when spin is present. The gyro structures can be biased by centrifugal forces, thus limiting the measurement capability. Testing is presently underway using the ARL 3-DOF flight simulator (D'Amico 1984). The present, first-generation device is shown in Figure 8, and the ARL flight simulator is shown in Figure 9.

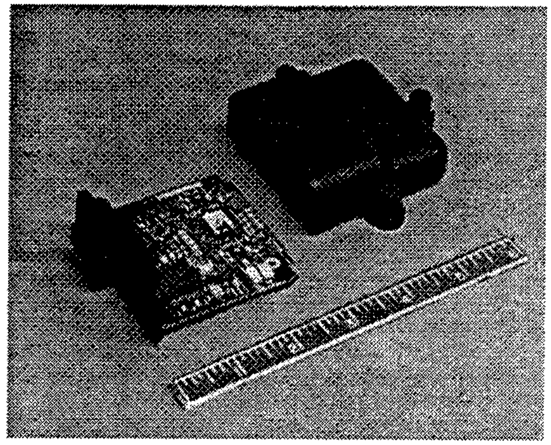


Figure 8. MEMS Gyroscope From Boeing/Draper.

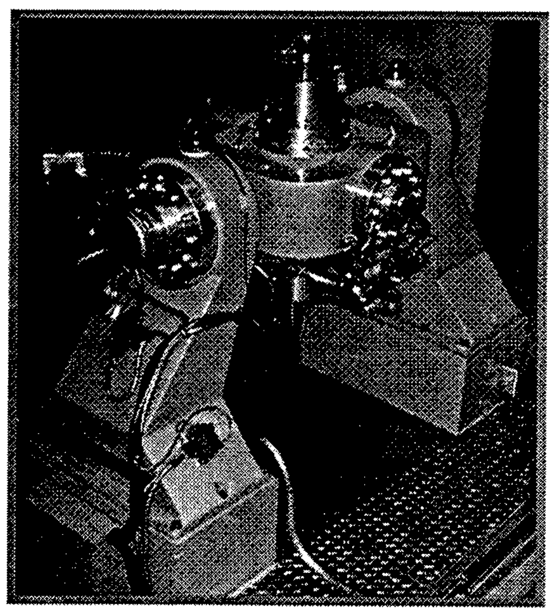


Figure 9. ARL Flight Simulator for Spinning Projectiles.

At present, a very unique non-MEMS, angular-rate sensor is available from ATA Sensors. The operational concept relies on the relative motion between a conductive fluid and a permanent magnet. This sensor has been designed to withstand high shocks and to measure very high and rapidly changing angular rates. It is relatively small, but it is larger than the MEMS accelerometers. Preliminary testing has shown essentially no effect of spin on the measurement of angular rate. Additional tests are being conducted on the ARL 3-DOF flight simulator, where very high spin rates and realistic angular motion common to artillery projectiles can be reproduced. A typical ATA sensor is shown in Figure 10.

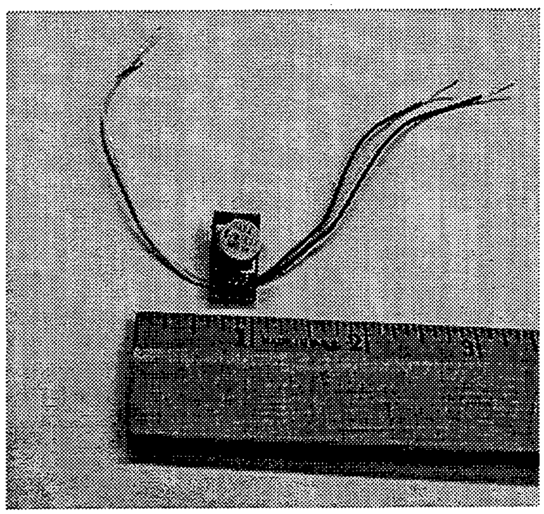


Figure 10. Magnetohydrodynamic Angular-Rate Sensor.

11. Pressure Transducers

Only a few projectile free-flight experiments have been successfully conducted with pressure transducers. Two difficulties were that the flight hardware was highly customized and the gauges were problematic. Again, MEMS manufacturing technologies are capable of providing new solutions. There are several MEMS pressure transducers designed for use in automotive fuel systems. These sensors have operational characteristics typically in the atmospheric range (not to exceed 100 psia). The HSTSS and CTIP programs have just begun initial ground testing of theses devices, and flight tests are expected next year. There is, however, a critical need for routine measurements of very high pressures during the launch cycle of projectiles.

11.1 Surface Pressure Measurements for Spinning Projectiles. A series of free-flight pressure measurements was initiated by Mark (1977, 1979). One effort provided base pressure data for gun-launched cones (Mark 1979), and the other was for a spinning, wind-tunnel model (Mark 1977). Specially constructed, diaphragm, strain-gauge pressure transducers were used in both cases. The relatively miniature sensors used mechanical stops to prevent short duration but large overpressures from destroying the gauges. These experiments indicated promise. In the case of the wind-tunnel model, the data were initially misinterpreted due to phase errors in the data demodulation process. This was corrected (D'Amico 1980), subsequently leading to a more aggressive series of tests to demonstrate the survivability and accuracy of these types of pressure gauges for use on spinning 155-mm projectiles (Kayser, Clay, and D'Amico 1986). Initially, there were great concerns that the gauges would also sense centrifugal acceleration and require some type of compensation or that the gauges would have to be located on the spin axis with a complex system of ports to communicate the external flow to the gauge. In short, the experimental data for gauges located either directly on the conical ogive surface or at radial or centerline locations within the ogive were in agreement. The gauge and data link system had been demonstrated, but advances in computational fluid dynamic (CFD) techniques limited the use of the methodology.

11.2 Motor Pressure/Temperature Measurements for the 155-mm M864. The previous experiences of pressure measurement were revisited again when the projectile community needed detailed information on the motor pressure and temperature and projectile base pressure for base-bleed projectiles. In had been common practice to employ base-located rocket motors to extend the range of projectiles. Ground tests for relatively standard motor/nozzle systems have successfully led to the militarization of rocket-assisted projectiles (RAP). Due to residual yaw disturbances subsequent to launch, these RAP motors are not ignited until a few seconds downrange. If that were not the case, then small components of the thrust would act normal to the flight path due to launch yaw disturbances, thus reducing accuracy. The base-bleed approach, however, can be initiated during the in-bore cycle and can provide drag reduction at launch. This method simply provides a low-velocity stream of hot gases that are released into the base flow/wake region with the intent of recovering a portion of the base pressure. The motor grain burn rates are a function of the base pressure, motor temperature, and spin. A simultaneous simulation of all three effects was virtually impossible in a ground test. Hence, a series of flight tests was designed.

Kayser, Kuzan, and Vazquez (1988, 1991) performed such a series of ground and flight tests, where extensive modifications were made to the entire projectile. A system of ports and seals was designed to preclude the attenuation and/or phase delay of the pressure signal from the exterior of the projectile base and within the motor chamber. Additionally, a thermocouple probe was fabricated and inserted into the motor chamber. It was realized that the temperature measurement would be crude due to corrosive products that would build up on the probe, but a temperature measurement was needed. All of the pressure transducers were located in the interior of the base region of the projectile, and all signals were carried forward along the interior length of the projectile to the ogive where another surface pressure measurement and a yawsonde system were located. All aft and forward signals were mixed and broadcast by a nose-located transmitter-antenna combination. The motor pressure and temperature data were invaluable as estimates provided to CFD models. Data from these flight tests for external base pressure were in excellent agreement with the CFD predictions.

11.3 Tracer-Well Telemetry System for a Direct-Fire Projectile. The instrumentation of artillery projectiles is difficult, but there is also a need to provide in-flight data for tank-fired ammunition, so-called direct-fire projectiles. Typically, these munitions afford less volume for instrumentation (virtually none for a KE projectile) and have higher launch accelerations (although they are mostly fired from smoothbore guns that do not result in high spin rates at launch). A common feature of direct-fire projectiles is that a tracer is located in the rear of the munitions that is ignited during the in-bore cycle. This tracer provides a visual-tracking aid to the gunner. It would be possible to replace the tracer with a telemetry system.

An effort was made by an industry-government team to demonstrate the potential of such a tracer-well system (Burdeshaw and Clay 1991). An antenna, transmitter, power supply, and g-switch were assembled into a "plug" and successfully tested using a 105-mm tank projectile and gun. No sensors were included, but spin data were obtained from the amplitude modulation of the received telemetry automatic gain control (AGC) signal as the antenna (and the associated radiation pattern) spun during the flight. This system showed that the telemetry system could survive the launch acceleration and the in-bore thermal and pressure pulses. The antenna located on the rear face of the tracer necessitated a very high and nonstandard transmitter frequency and a unique, noncommercial telemetry receiver. Hence, the effort was not continued until a range-compatible system was devised.

Recently, a new tracer-well telemetry system has been demonstrated under the HSTSS program, where a standard S-band transmission frequency was used with a spin sensor (the GMR spin sensor described previously). As before, a 105-mm tank gun-projectile combination was used. GMR spin data were corroborated by using the telemetry AGC signals. The cost of all the raw electrical components was less than $600. This demonstration provides a dramatic example that very miniature and expensive systems can be designed to survive and operate in hostile environments. The tracer well concept is shown in Figure 11.

12. Summary

The examples and concepts presented here are intended to demonstrate that miniature, rugged, inexpensive telemetry systems can be effectively built and used. In a real sense, the previous complexity and expense of instrumented free-flight testing techniques probably placed an unreasonable burden on aerodynamic ground test facilities and techniques. The ability to conduct realistic flight tests on actual prototypes should be viewed as part of a coordinated effort to efficiently and realistically test new projectile and munitions concepts.

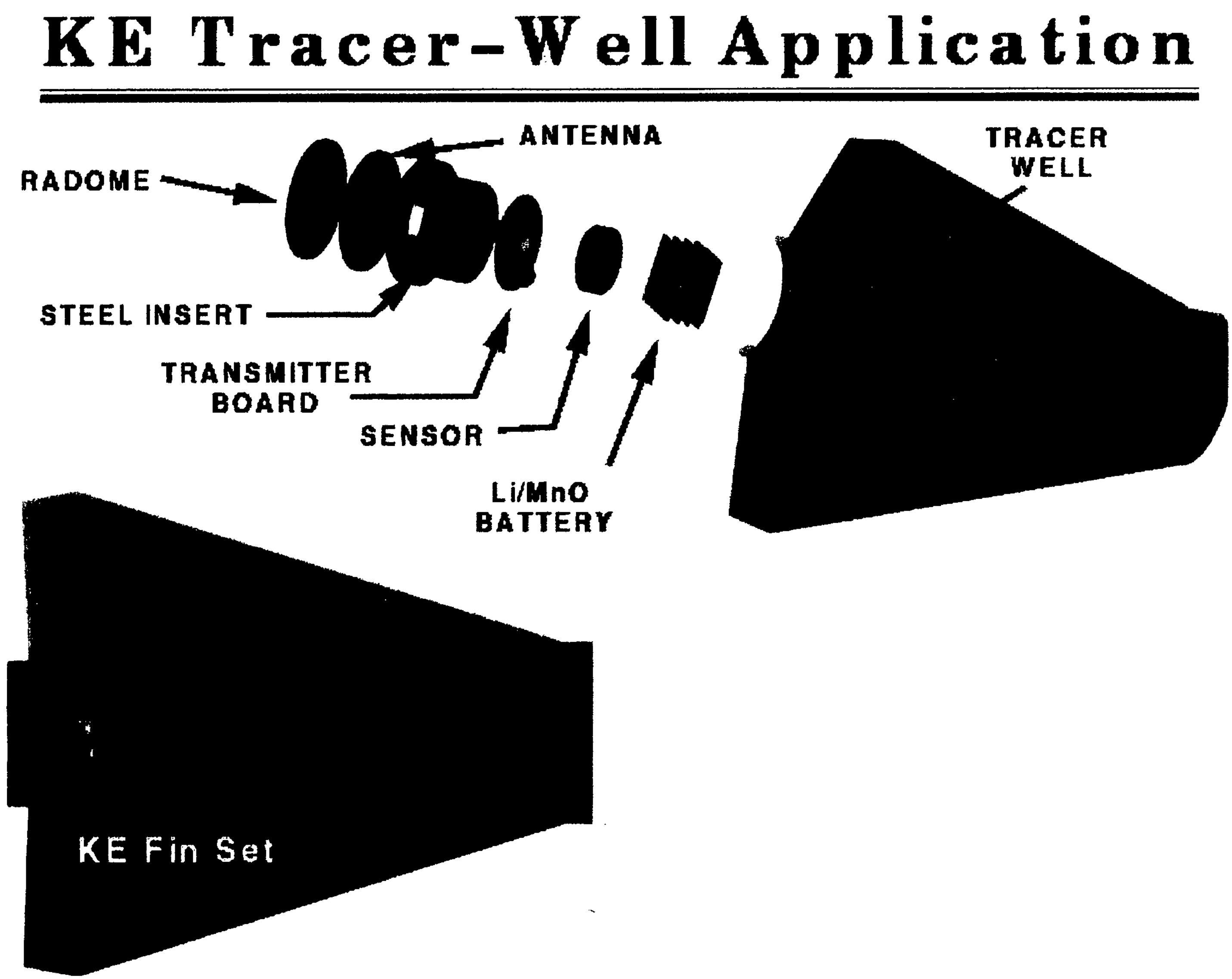


Figure 11. HSTSS Concept Tracer-Well Instrumentation Package.

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A survey of telemetry techniques for miniature and high-g applications is provided. The sum of many individual efforts is providing an expanding set of tools and techniques by which a new generation of flight tests is possible. Additionally, major thrusts have been made to substantially reduce the cost of key components and modules of the telemetry system. New capabilities in transmitters, power supplies, electronic packaging, and sensors are being developed.

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